Vertical Structure of Shadow Zone Arrivals:
Comparison of Parabolic Equation Simulations and Acoustic Data

Lora J. Van Uffelen
Scripps Institution of Oceanography
University of California, San Diego
9500 Gilman Drive, Mail Code 0238
La Jolla, CA 92093-0238
phone: (858) 822-4908   fax: (858) 534-6251   email: lvanuffe@ucsd.edu

LONG-TERM GOALS

As part of the North Pacific Acoustic Laboratory (NPAL) program, the long-term goals of this project are to understand the physics of long-range, broadband propagation in deep water and the effect of oceanic variability on acoustic propagation.

OBJECTIVES

Observations made during the Acoustic Thermometry of Ocean Climate (ATOC) experiment show that acoustic energy penetrates significantly deeper in the water column below the lower turning points of the predicted acoustic ray paths than is expected from diffraction alone [1]. This energy appears anomalously deep in the water column, but the measured travel times seem to correspond well with timefronts predicted to have cusps several hundred meters above the depth of the receivers.

The objective of this particular effort is to examine the vertical structure of these "shadow-zone arrivals" and to determine the relative roles of different sources of oceanic variability such as internal waves, ocean spice, and reflections off the base of the oceanic mixed layer in contributing to the vertical scattering.

APPROACH

In June 2004, two source moorings and a set of hydrophone arrays were deployed in the North Pacific Ocean as part of the SPICEX experiment. (SPICEX was one component of the larger 2004 NPAL experiment, which also included the Long-range Ocean Acoustic Propagation EXperiment (LOAPEX) and the Basin Acoustic Seamount Scattering EXperiment (BASSEX).) The two closely spaced vertical line arrays (VLAs) together virtually spanned the full ocean depth, enabling observation of the vertical structure of the timefront arrivals.

The two source moorings were located at ranges of 500 km and 1000 km from the VLAs, each supporting acoustic sources at both 750 meters, the approximate depth of the sound channel axis, and 3000 meters, slightly above the surface conjugate depth. Receptions from all four sources were analyzed to determine the level of scattering into the shadow zone.

1. REPORT DATE **30 SEP 2008**	2. REPORT TYPE **Annual**	3. DATES COVERED **00-00-2008 to 00-00-2008**

4. TITLE AND SUBTITLE **Vertical Structure Of Shadow Zone Arrivals: Comparison Of Parabolic Equation Simulations And Acoustic Data**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of California, San Diego,Scripps Institution of Oceanography,9500 Gilman Drive, Mail Code 0238,La Jolla,CA,92093-0238**	8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
code 1 only

14. ABSTRACT
As part of the North Pacific Acoustic Laboratory (NPAL) program, the long-term goals of this project are to understand the physics of long-range, broadband propagation in deep water and the effect of oceanic variability on acoustic propagation

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

The experimental data were compared with parabolic equation propagation simulations based upon hydrographic measurements taken at the time of the deployment [2]. Three different environments were considered: a range-dependent profile developed using underway CTD (UCTD) measurements taken at the time of the experimental deployment, the mean sound-speed profile, and a mean sound-speed profile perturbed to stochastically simulate the oceanic sound-speed perturbation due to internal waves [3].

Previous work on the SLICE89 data has shown that internal waves break down the geometrical optics timefront pattern and broaden the timefront at the finale [4]. It has also been hypothesized that reflections off the base of the mixed layer may cause a steepening and deepening of acoustic rays that increases with the number of reflections from the base of the mixed layer [5]. Spicy fronts within the mixed layer may also contribute to scattering into the geometric shadow zone. Simulations have been performed to predict this scattering, but have not been compared to acoustic data [6].

This work is funded as a graduate student traineeship award. The members of my thesis advisory committee, Dr. Peter Worcester (chair), Dr. Bruce Cornuelle, Dr. Daniel Rudnick, Dr. Walter Munk and Dr. William Kuperman, all of the Scripps Institution of Oceanography, Dr. Kathleen Wage of George Mason University, and Dr. William Coles of the electrical engineering department at the University of California, San Diego, are providing advice and guidance as committee members. Dr. Matthew Dzieciuch of the Scripps Institution of Oceanography has also contributed.

WORK COMPLETED

Because acoustic travel time is the primary observable utilized in ocean acoustic tomography, previous analysis of long-range propagation data has focused on acoustic travel time, with less attention paid to determining the intensity of arrivals. Determining the absolute intensities of both acoustic data and parabolic equation simulations is necessary to make meaningful comparisons between acoustic receptions, as well as between receptions and simulation data.

The VLA receivers were fully calibrated. The intensities of the measured receptions were calculated using the measured hydrophone sensitivity and VLA system gain, taking account of the signal processing gains achieved using the large time-bandwidth signals. The predicted intensities of the receptions were calculated using the measured source functions and transmission losses from broadband parabolic equation simulations.

These calibrations enabled direct intensity comparisons of daily incoherent averages of hydrophone data with Monte Carlo parabolic equation simulations incorporating several realizations of stochastic internal-wave fields. The comparisons presented here are largely qualitative, although preliminary quantitative measures describing the energy in the shadow-zone arrivals for both simulation and data have been calculated. A more detailed quantitative analysis of the statistics of the shadow-zone extensions, as well as the characterization of their variability throughout the transmission period, will be left for future examination.

RESULTS

The intensity comparisons presented here demonstrate that models incorporating sound-speed fluctuations consistent with the Garrett-Munk internal wave spectrum (1GM) are adequate to describe the observed structure and extent of measured acoustic shadow-zone arrivals.

The results focus on a single day of acoustic transmissions at a time coinciding with the collection of the environmental data that formed the basis for the sound-speed profiles used in the simulations. Calculations were made for all eight source-receiver pairs. This report will focus on the transmission path from the sources located at 1000-km range to the deep segment of the VLA.

Axial Source

The 1000-km propagation path from the axial source provides several examples of shadow-zone extensions. The most prominent of these extensions are the second pair of lower turning points, arriving immediately after 675 seconds (Figure 1).
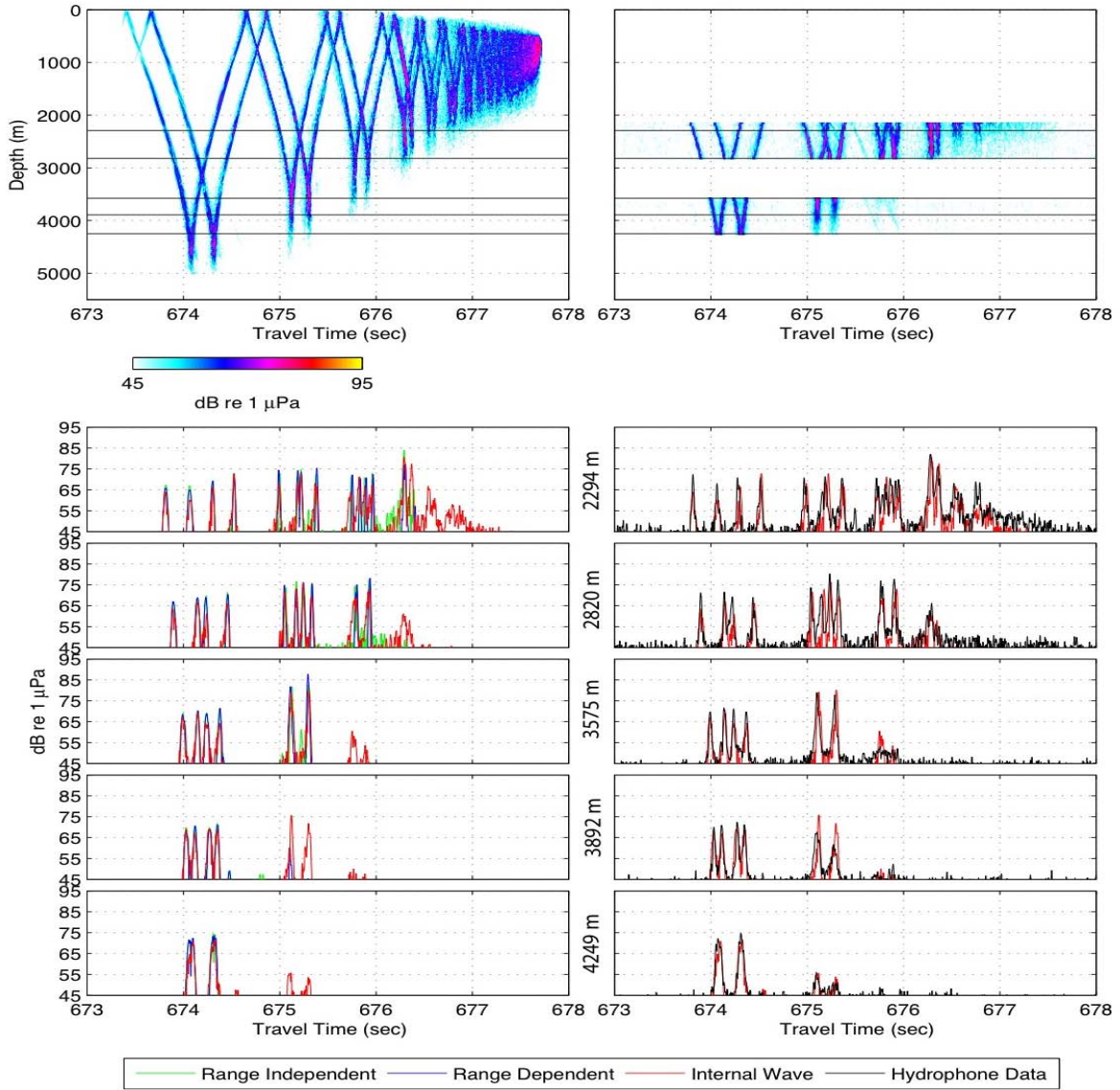
Figure 1: Intensity-averaged PE simulations for the 1000-km path from an axial source to the deep portion of the VLA incorporating five realizations of 1 GM internal wave fields (top left), and an intensity average of six receptions of acoustic data received on yearday 167 (top right). Horizontal black lines indicate depths where slices of the internal wave PE simulation timefront are compared with similar range-dependent and range-independent predictions (lower left) and acoustic hydrophone data (lower right).

The range-independent prediction is consistent with the internal wave prediction at 3575 meters, but does not extend to the hydrophone at 3892 meters. The internal wave simulation, however, exhibits a 75-dB arrival at this depth for the first cusp of the pair, and both cusps reach the lowest limit of the VLA. Although the measured intensities compare well with internal-wave simulations at the 3575 and 4249-meter depths, internal wave scattering over-predicts the intensity of the shadow-zone arrival by approximately 8 dB when compared with the hydrophone data at the 3892-meter depth.

This deviation is more easily seen in Figure 2, which displays a measure of the energy in the cusp as it extends into the acoustic shadow. The upper limit of the shadow zone is located where the energy for the range-independent calculation rapidly decreases. The internal wave simulation appropriately describes the shadow-zone arrivals below both cusps with rms differences from the measured energy levels of 2.5 dB for the first cusp and 4.0 dB for the second cusp.
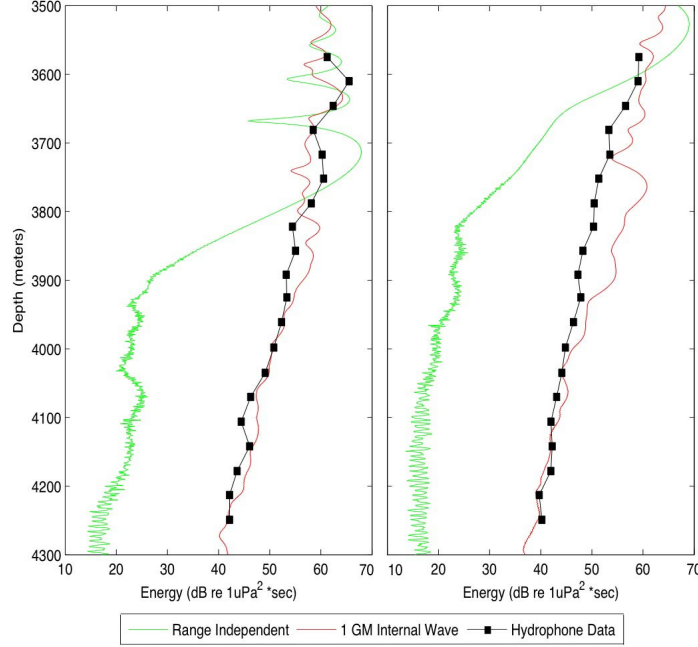

Figure 2: Energy in the pair of lower cusps occurring after 675 seconds for the axial source and a 1000-km propagation path. Energy was calculated for a time window of 675.0 to 675.2 seconds for the first cusp (left) and 675.2 to 675.4 seconds for the second cusp (right). Hydrophone data is shown for the 20 deepest phones on the VLA.

Off-Axis Source

Receptions from the off-axis source at 1000-km range illustrate the same deep shadow-zone arrivals as exhibited by the axial source. One such shadow-zone extension arrives at approximately 675.5 seconds on the lower segment of the VLA (Figure 3).
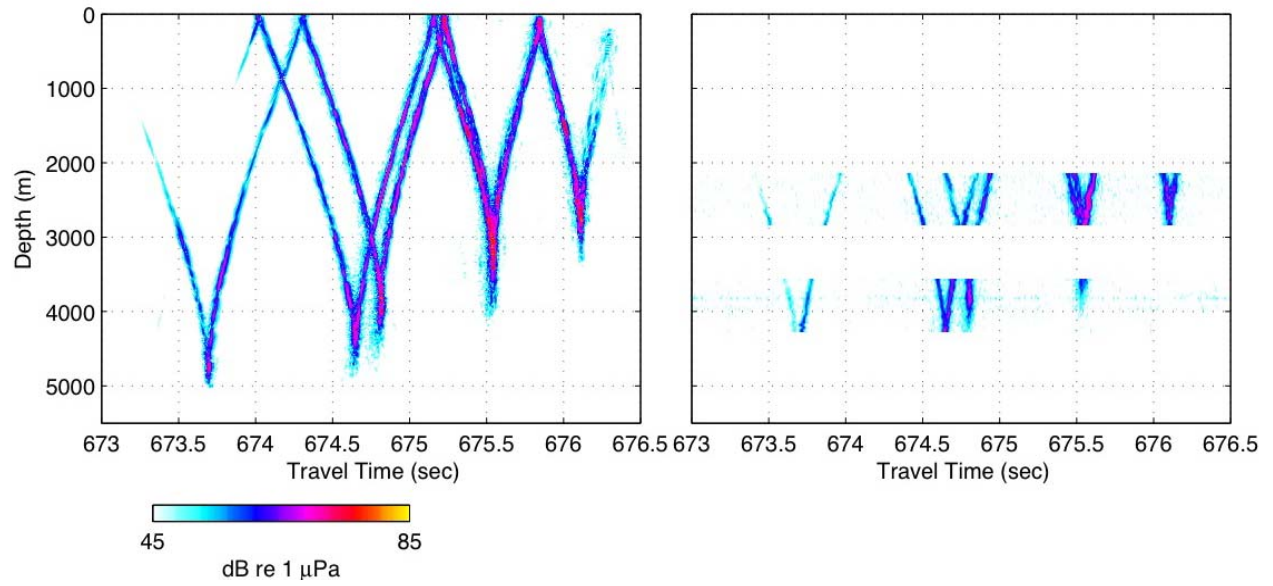
Figure 3: Intensity-averaged PE simulations for the 1000-km path from an off-axis source to the deep portion of the VLA incorporating five realizations of 1 GM internal wave fields (left) and an intensity average of six receptions of acoustic data received on yearday 167 (right).
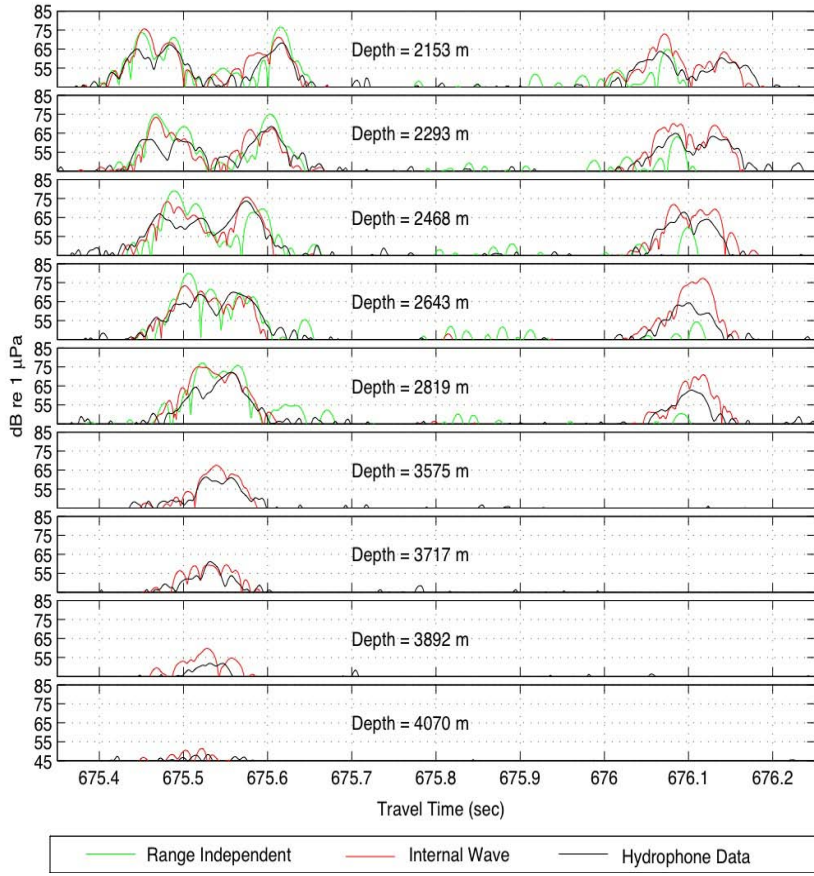
Figure 4: Magnification of two lower cusps on the 1000-km propagation path from the deep source to the deep VLA segment. Simulations utilizing range-independent and internal wave environments are included along with the hydrophone data. Data are shown at the depths of 9 hydrophones.

Figure 4 summarizes the shadow penetration this cusp. At depths less than 3 km, measured intensities are in fair accord with the calculated intensities ignoring internal wave scatter. Taking internal wave scatter into account does not significantly change the theoretical intensities above 3 km, but increases the theoretical intensities substantially beneath 3 km, bringing them into accord with the measured intensities. Beneath 4 km both measured and computed intensities are negligible. From this, it can be concluded that the internal wave perturbations can account for the penetration into the deep shadow zone.

In addition to deep shadow-zone extensions, the receptions from the off-axis source reveal scattering back up towards the axis at the end of the arrival pattern, which is not predicted by range-independent models, indicating another type of shadow zone at the end of the arrival pattern. This scattering occurs predominantly along acoustic timefronts, which is consistent with the observations of scattering for deep shadow-zone arrivals. The beginning of one such axial shadow-zone extension is displayed in Figure 3 at the termination of the observed arrival pattern.

Figure 4 demonstrates that internal wave perturbations also account for these axial shadow-zone extensions. The two arrival peaks at 676.1 seconds for the phones at 2293 and 2153 meters depth

7

clearly show the internal wave simulation to concur with the hydrophone data in scattering back towards the axis along the timefront.

IMPACT/APPLICATIONS

This research has the potential to affect the design of deep-water acoustic systems, whether for sonar, acoustic communications, acoustic navigation, or acoustic remote sensing of the ocean interior.

RELATED PROJECTS

A large number of investigators and their students are currently involved in ONR-supported research related to the NPAL project. The Principal Investigators include R. Andrew (APL-UW), A. Baggeroer (MIT), F. J. Beron-Vera (UMiami), M. Brown (UMiami), J. Colosi (NPS), B. Dushaw (APL-UW), N. Grigorieva (St. Petersburg State Marine Technical Univ.), K. Heaney (OASIS), F. Henyey (APL-UW), B. Howe (APL-UW), J. Mercer (APL-UW), A. Morozov (WRC and WHOI), V. Ostachev (NOAA/ETL), D. Rudnick (SIO), E. Skarsoulis (IACM/FORTH), R. Stephen (WHOI), A. Voronovich (NOAA/ETL), K. Wage (George Mason Univ.), and M. Wolfson (APL-UW).

REFERENCES

[1] Dushaw, B. D., Howe, B.M., Mercer, J.A., Spindel, R.C., and The ATOC Group (A. B. Baggeroer, T. G. Birdsall, C. Clark, J. A. Colosi, B. D. Cornuelle, D. Costa, B. D. Dushaw, M. A. Dzieciuch, A. M. G. Forbes, B. M. Howe, D. Menemenlis, J. A. Mercer, K. Metzger, W. H. Munk, R. C. Spindel, P. F. Worcester, and C. Wunsch) (1999). "Multimegameter-Range Acoustic Data Obtained by Bottom-Mounted Hydrophone Arrays for Measurement of Ocean Temperature," IEEE Journal of Oceanic Engineering **24**, 202-214.

[2] Collins, M.D. (1989). "A higher-order parabolic equation method for wave propagation in an ocean overlying an elastic bottom," J. Acoust. Soc. Am. **86** 1459-1464.

[3] Colosi, J.A., Brown, M.G. (1998). "Efficient numerical simulation of stochastic internal-wave-induced sound-speed perturbation fields," J. Acoust. Soc. Am. **103**, 2232-2235.

[4] Colosi, J.A., Flatte, S.M., Bracher, C. (1994). "Internal-wave effects on 1000-km oceanic acoustic pulse propagation: Simulation and comparison with experiment," J. Acoust. Soc. Am. **96**, 452-468.

[5] Rudnick, D.L. and W. Munk (2006). "Scattering from the mixed layer base into the sound shadow," J. Acous. Soc. Am. **120**, 2580-2599.

[6] Dzieciuch, M.A., Munk, W., Rudnick, D.L. (2004). "Propagation of sound through a spicy ocean, the SOFAR overture," J. Acoust. Soc. Am. **116**, 1447-1462.

PUBLICATIONS

Van Uffelen, Lora J., Worcester, Peter F., Dzieciuch, Matthew A., Rudnick, Daniel L. "The Vertical Structure of Shadow-Zone Arrivals at Long Range in the Ocean," J. Acoust. Soc. Am, submitted.